Pressurisation of fixed roof storage tanks due to external fires

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PRESSURIZATION OF FIXED ROOF STORAGE TANKS DUE TO EXTERNAL FIRES

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INTRODUCTION

This study deals with one of the phenomena which is able to generate fire balls like the one which was observed during the 1987 Edouard Herriot port of Lyon fire. Reflections led on this accident have pushed to consider the phenomenon of tank pressurization as a potential initiating event of the fire ball observed. In concrete terms, when a fixed roof storage tank is surrounded by a pool fire, and when the vents or the insulation are not correctly designed, the inside pressure can raise until the mechanical limits of the structure are reached. The aim of this study is to develop a tool which will allow to follow the variations of the pressure and temperature in the gas phase, highlighting if a pressure increase is possible or not. This will help the sizing of new tank vents and insulation of the walls, or evaluating the risk of already build structures, by solving the question occurrence of the accident, regarding the estimated external fire duration. The model also gives the temperature distribution in the liquid phase, at each time step. In case of rupture, this information will be useful to describe the phenomenological aspect of the accident after the rupture of the tank. It means that qualifying and quantifying the fire ball generated and its effect on persons and structures will be possible. Currently, although a few analytical models exist to quantify the fire ball and its effects after the rupture, none is able to describe with accuracy the pre-rupture phenomena. This model is a work in progress, and at the end, the tool will take into account the two phases of the accident and will allow to study complete and consistent scenarios. After a description of the numerical model developed, this paper presents its application on the study of the influence of various parameters.

DESCRIPTION OF THE MODEL AND INPUT DATA

The modelling tool presented is a dynamic model which represents the axisymmetric behavior over time of a cylindrical tank, when this one is impacted by a pool fire. The approach which has been followed in all building steps of the model was to "forget" the empiric assumptions, laws or formulas used in current standards, and to consider only the basic equations of thermodynamic and fluids mechanic. As the literature doesn't present experimental tests or accidents analysis allowing to check the evolution of different parameters, it is essentially the study of energy balance and trends evolutions which have been considered to validate each step of conception of the model. The heat transfers taken into account in the model are represented on Figure 1.

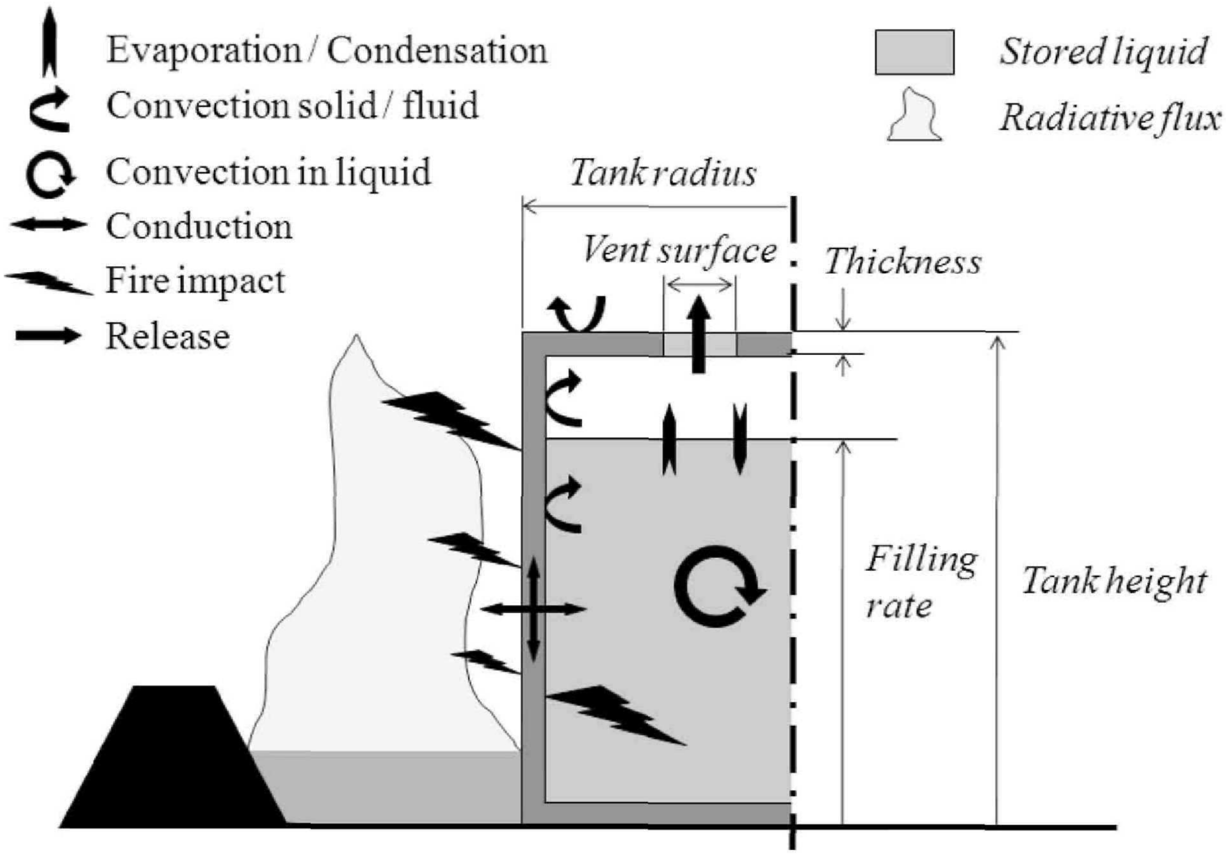

Figure 1. Input data and considered heat transfers

As stated previously, the studied geometry is considered axisymmetric. The input parameters written in italic on Figure 1, are the specific dimensions of the tank: its height, diameter and thickness. The thickness of the wall is supposed uniform. It's also necessary to input the filling rate of the tank, expressed as a percentage. The vent itself is defined by its surface and its discharge coefficient. A minimum opening pressure must also be provided. This latter parameter allows to take into account the safety valves. It is possible to consider several substances: water, ethanol, hexane (C_6), decane (C_{10}), undecane (C_{11}) or dodecane (C_{12}). In all cases, the substance is considered pure. The characteristics of the substances are intrinsic functions of temperature. To model the fire that impacts the tank, the radiative flux per unit area of flame must be defined. It is possible to define two types of aggression: a uniform distribution of the radiative flux along the entire height of the flame, or a radiative flux function of the height. In all cases, the flame height is limited to the height of the tank.

MESH

The mesh put in place is axisymmetric. The volume of liquid is divided into m x n identical sub-volumes. There are m volumes along the height, and n following the radius of the tank. So as to work with volumes of the same capacity, the spatial distribution is done following the equations **(1)** and **(2)** :

$$\Delta z = \frac{H_l}{m} \quad \textbf{(1)}$$

$$\Delta x = \frac{D}{2}\left(\sqrt{\frac{n-i+1}{n}} - \sqrt{\frac{n-i}{n}}\right) \quad \textbf{(2)}$$

The gas is supposed to have homogeneous pressure and temperature on the entire free volume. Therefore, it is composed of a single computational cell. As for the walls of the tank, it is represented with m+1 cells along the height, with a width along the radius equal to the thickness of the wall, as shown in Figure 2.

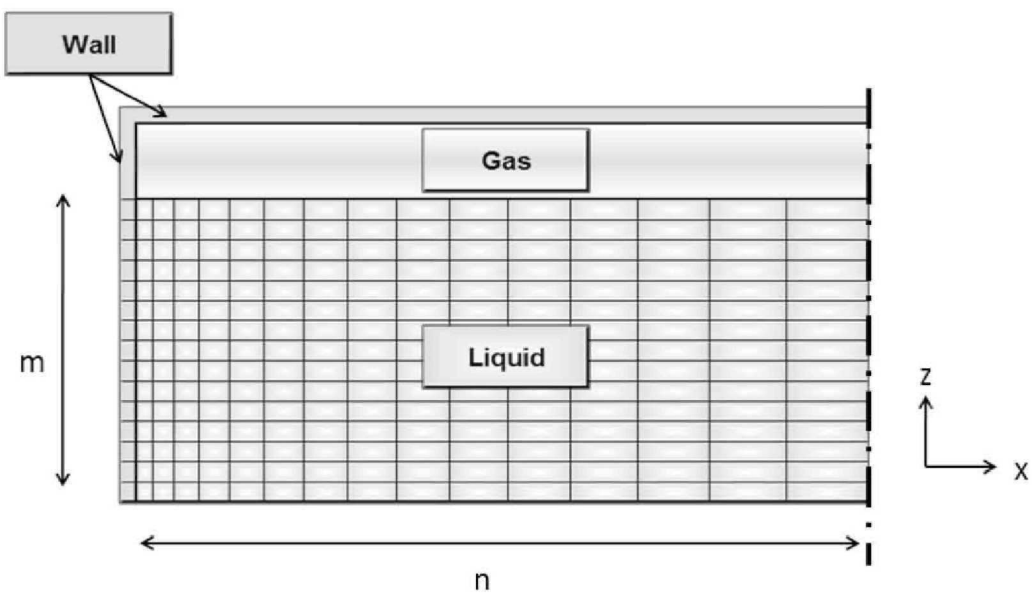

Figure 2. Axisymmetric mesh used

HEAT TRANSFERS

Thermodynamics allows us to predict the total amount of energy that a system should share with the outside to move from one equilibrium state to another. Thermokinetic is used to describe quantitatively the changes in characteristics of the system, particularly temperature, between the initial state of equilibrium and final steady state. At each time step, the calculation of heat transfers leading to a variation of pressure in the gas phase is done. The Figure 3 shows which equations are used in each cell so as to equilibrate the energy balance. The numbers in this Figure refers to the numbering of equations which are all defined later in the paper.

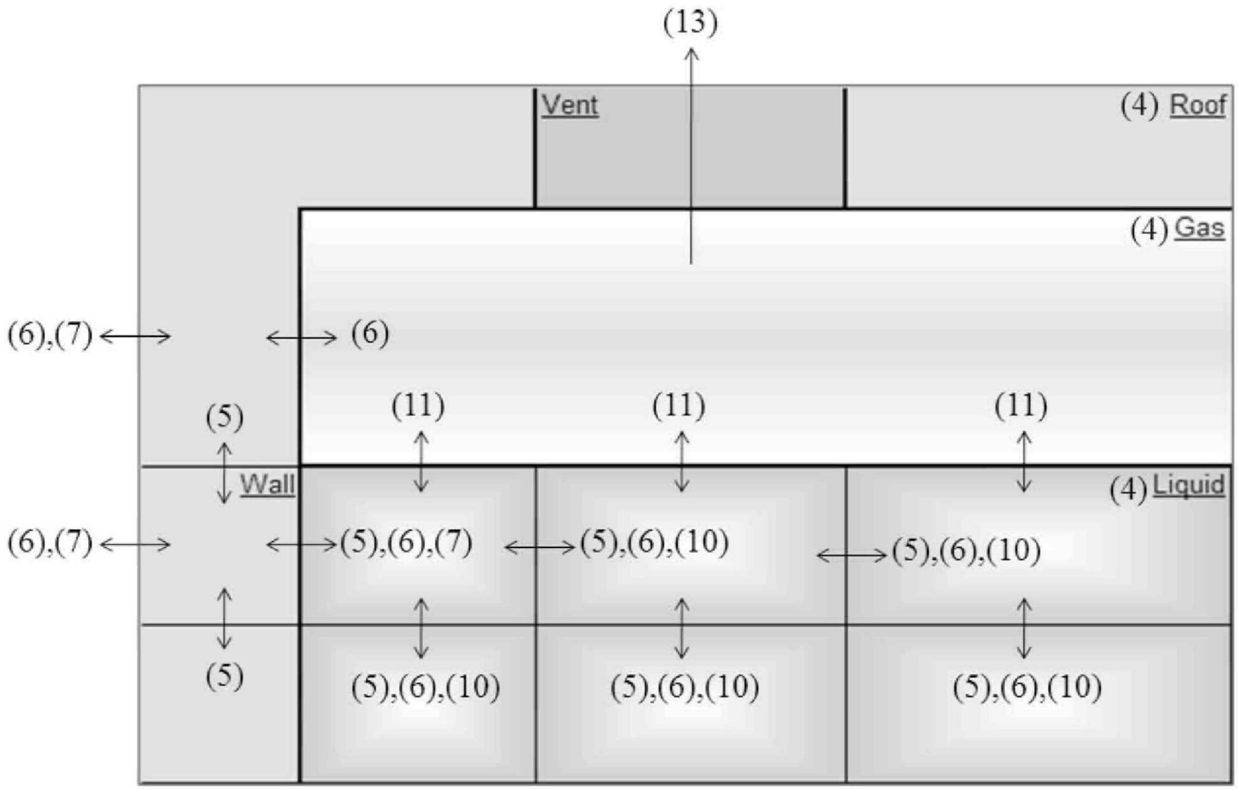

Figure 3. Equations taken into account

The various equations used correspond to the first thermodynamic law applied to each defined system, i.e. to the following energy balance:

$$\varphi_i + \varphi_{ge} = \varphi_o + \varphi_{st} \qquad \textbf{(3)}$$

With φ_i the incoming heat flux, φ_{ge} the generated heat flux, φ_o the outgoing heat flux, φ_{st} the stocked heat flux. Solving this equation leads to a differential equation which allows to determine the evolution of the temperature at a given point during time. The heat flux are calculated the following ways:

- ***The generated heat flux:*** it occurs when another form of energy (chemical, electrical, mechanical, nuclear) is converted into thermal energy. The system considered here is not concerned by this type of flux.
- ***The stocked heat flux:*** it is linked to an augmentation of the internal energy of the system during time. It can be written as **(4)**:

$$\varphi_{st} = \rho V C \frac{\partial T}{\partial t} \qquad \textbf{(4)}$$

- ***The incoming and outgoing heat flux:*** heat transfers can occur by:

Conduction: it is the favorite way of energy transfer in opaque medium. It occurs without material movement, along the temperature gradient. It is calculated following the Fourier hypothesis (for example in the x direction) by the equation **(5)**:

$$\varphi = -\lambda S \frac{\partial T}{\partial x} \tag{5}$$

Convection: it is the transfer of heat between a solid and a fluid, obtained by the displacement of the fluid. This phenomenon is governed by the Newton law **(6)**:

$$\varphi = hS(T_P - T_\infty) \tag{6}$$

Radiation: it is an electromagnetic transfer of energy between two surfaces. It is calculated with the equation **(7)**:

$$\varphi = \sigma \varepsilon_P S \left(T_P^4 - T_\infty^4\right) \tag{7}$$

Evaporation, condensation and convection inside the liquid are important heat transfer modes. Taking them into account is more complex their modeling is detailed in the next sections.

CONVECTION ALGORITHM INSIDE THE LIQUID

The convection algorithm developed is based on the use of the dimensionless Grashof's number. A static fluid in contact with a wall brought from a temperature T to a higher temperature $T+\Delta T$, will overheat by conduction. The density of a fluid volume will increase from ρ to $\rho+\Delta\rho$. This unit volume will be subjected to a lifting force. While β is the cubic expansion coefficient, $\beta\Delta T$ represents the module of the acceleration produced by thermal expansion due to changes in temperature. This movement of fluid caused by differences in density will give rise to convection currents. By equalizing the variation of kinetic energy to the variation of potential energy, the number of Grashof allows to calculate the rising speed (ms^{-1}), for a unit volume of liquid:

$$Gr = g \frac{\Delta\rho}{\rho} \frac{L^3}{\mu^2} \tag{8}$$

$$u = \sqrt{2Gr} \frac{\mu}{\rho L} \tag{9}$$

This algorithm is based on the principle that the phenomenon of convection is initiated and amplified by the volume of liquid moving upward. The downward movements are the result of the imbalance caused. According to equation **(9)**, the fraction of volume which comes out of a cell is defined by:

$$dV = S_h \, dz = S_h \, u \, dt \tag{10}$$

Mass conservation law is used to define step by step, for each cell, the fraction of liquid volume entering or leaving the considered cell, as well as its origin or its direction. The contribution of convection for calculating the temperature of a fluid cell density can be determined following the approach detailed in Figure 4.

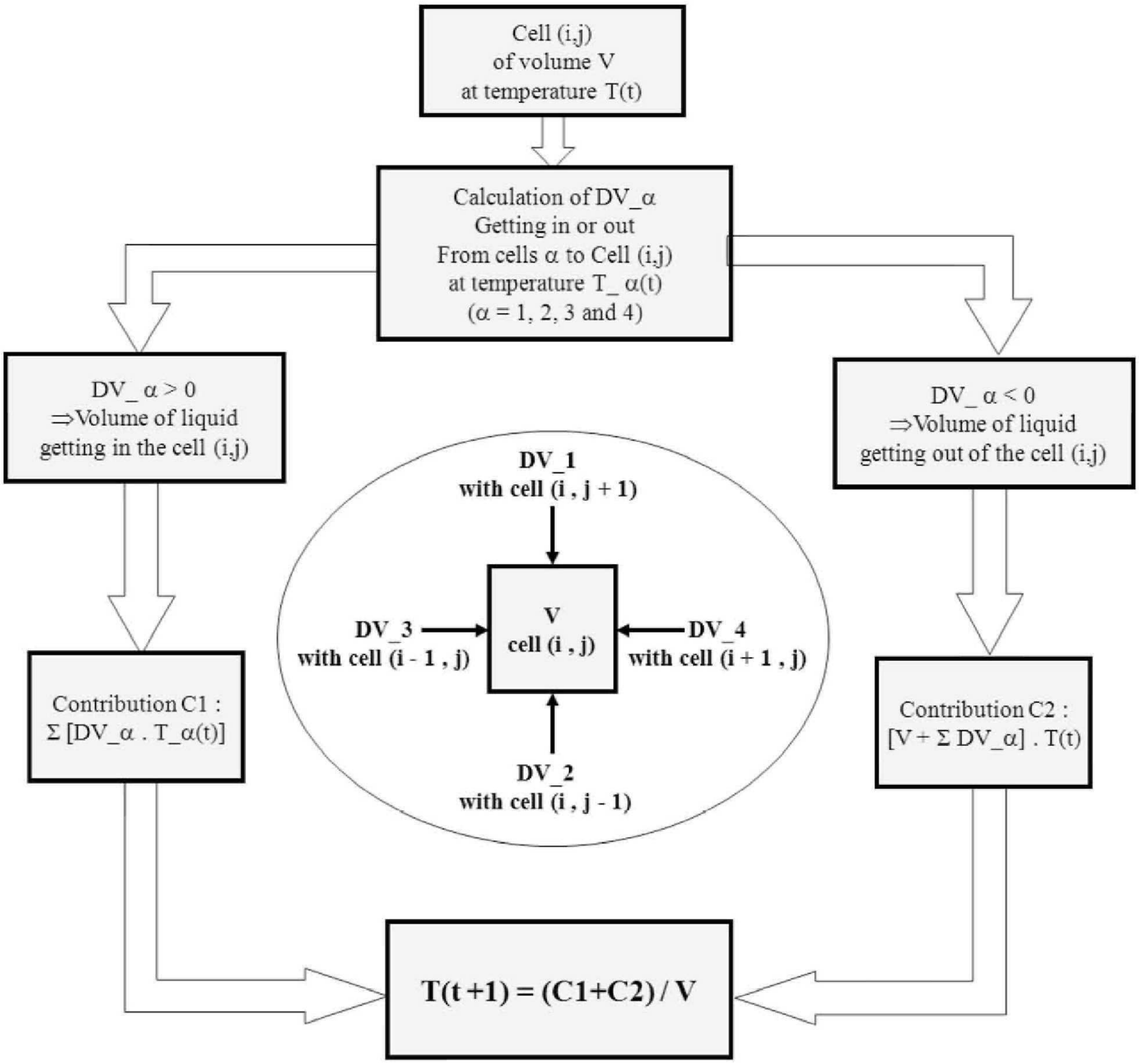

Figure 4. Participation of natural convection in liquid temperature calculation

INTEGRATION OF EVAPORATION AND CONDENSATION

At each time step, and for each cell volume, the vapor pressure at the liquid temperature is compared to the partial vapor pressure in the gaseous volume of the tank. This allows to evaluate the mass transfer between phases in order to determine the contribution of evaporation and condensation to variations of:

- Pressure;
- Liquid level;
- Temperature.

The total number of moles of liquid which have to be evaporated is calculated so that the balance is achieved between the liquid and gas phases. To do so, the equation **(11)** is used. In this formula, *B* represents the second virial coefficient.

$$N(i,j)=\frac{\left(P_{vap\_sat}-P_{partial\_vap}\right)V_g}{RT_g\left(1+\frac{B}{V_g}\right)} \quad \textbf{(11)}$$

Two cases may arise: either the cell (i, j) is likely to contribute to the change of mole number in the gas phase, and the algebraic value of N is calculated, or it isn't, and N is equal to zero. This approach prevents from the presence of liquid with temperature above the equilibrium temperature corresponding to the partial pressure in the gas.

TAKING THE VENT INTO ACCOUNT

The gas is composed of a mixture of air and vapor due to the evaporation of the liquid inside the tank. The pressure in the tank is a function of four interdependent parameters: the temperature of the gas mixture, the rate of evaporation/condensation, the flow rate of the vent, the liquid level. At each time step, evaporation contributes to the change in the partial pressure of vapor, and increasing the total pressure in the gas. When it reaches and exceeds the trigger pressure of the vent, a certain amount of gas is evacuated outside of the tank. This volume of matter is calculated with the Bernoulli's equation:

$$V_{evac}=2C_D S_{vent}\sqrt{\frac{\Delta P}{\rho}}\,\Delta t \quad \textbf{(12)}$$

With C_D the discharge coefficient of the vent, S_{vent} its surface and ΔP the differential pressure between the inside and the outside of the tank. Knowing the number of moles of liquid at a temperature $T_l(i,j)$ evaporated, and the number of moles of gas at temperature T_g evacuated by condensation or through the vent, it is possible to determine the contribution of gas transfers to the variations of gas temperature:

$$T_g(t+1)=\frac{\left(N_{mol\_vap}+N_{mol\_air}+N_{mol\_cond}-N_{mol\_évac\_vap}-N_{mol\_évac\_air}\right)T_g(t)+\sum N_{mol}(i,j)\,T_l(i,j)}{N_{mol\_vap}+N_{mol\_air}+N_{mol\_cond}-N_{mol\_évac\_vap}-N_{mol\_évac\_air}+\sum N_{mol}(i,j)} \quad \textbf{(13)}$$

INFLUENCE OF THE DIFFERENT PARAMETERS

So as to determine the influence of the accessible parameters on the behavior of the system, a reference case has been used. The parameters corresponding to this reference case are:

- The height of the tank: 14 m;
- The diameter of the tank: 24 m;
- The thickness of the walls: 10 mm;
- The filling ratio: 50% of the tank capacity;
- The substance: hexane;
- The vent surface: 0,1 m²;
- The maximal radiative flux of the fire: 50 kW.m^{-2}.

The variations of the pressure of the gas phase are presented in Figure 5. The maximum pressure obtained here is called Pmax_ref. Pmax_ref keeps the same value all along the present section.

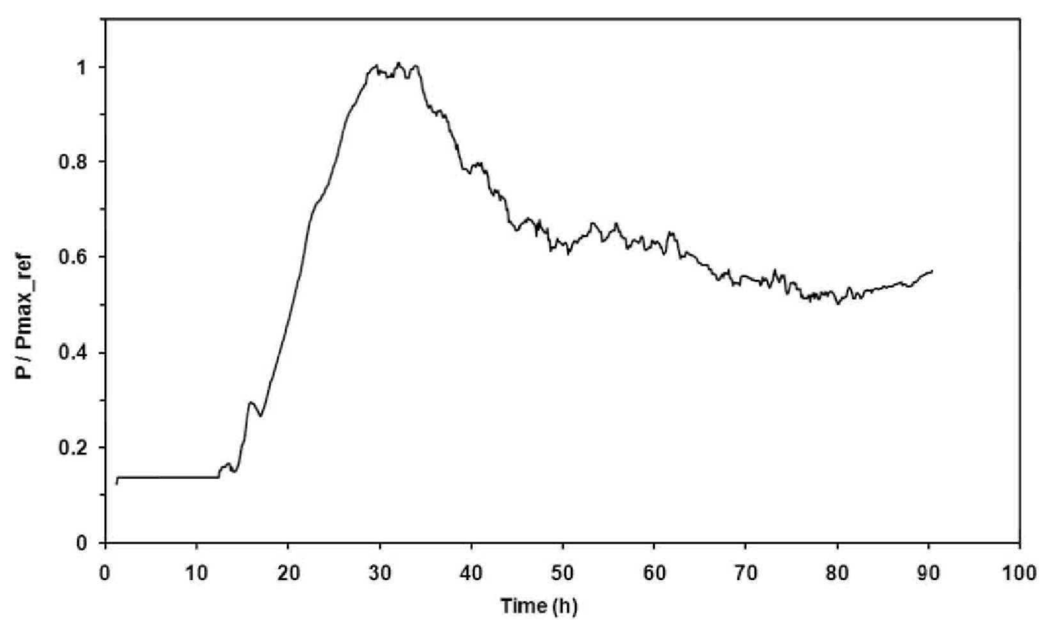

Figure 5. Evolution of pressure for the reference case

During the first 15 h, the size of the vent is sufficient to compensate the vaporization rate. The maximal overpressure is observed after 30 h of fire, where a 5 h plateau is reached. After, the pressure starts to decrease with the level of the liquid.

The influence of the followings parameters has been evaluated:

- The stored substance;
- The liquid level;
- The diameter of the tank;
- The vent surface.

The detailed graphs of the results obtained are presented from Figure 6 to Figure 9. They show the variation of the pressure in the gas phase when only one of the parameters previously defined varies. The blue curve is always the reference case.

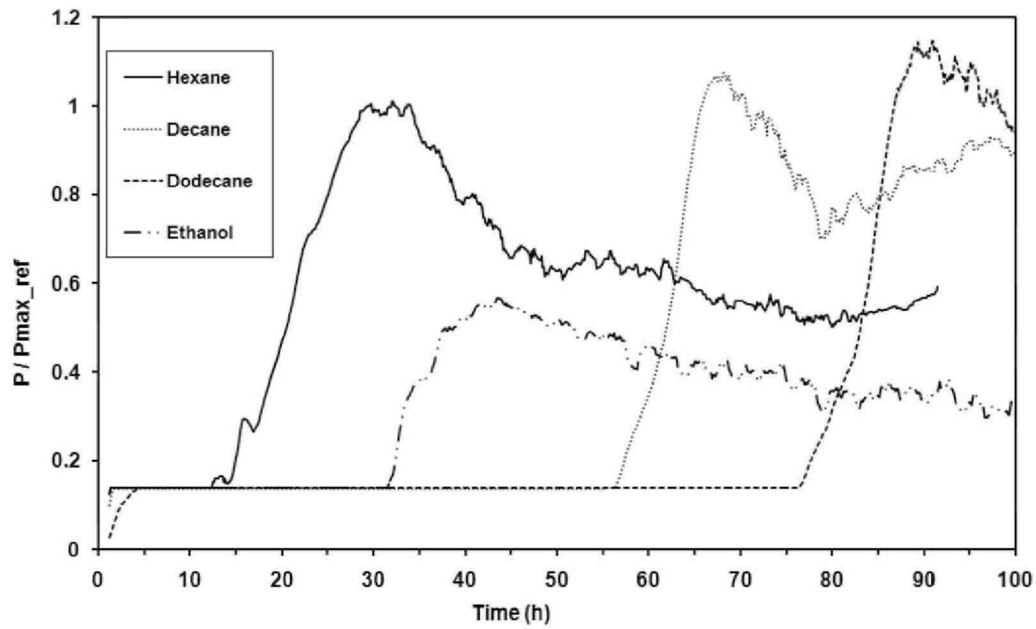

Figure 6. Influence of the substance stored

These curves show that for hydrocarbons, the overpressure is nearly the same in each case studied. The length of the carbon chain has an overall influence on the kinetic of the phenomenon. The pressure raise occurs later for the heavy substances than for the light ones. The case of a low molecular weight alcohol has been modeled too, and the results in this case show that the impact is also on the intensity of the overpressure.

The next parameter studied is the level of the liquid at the beginning of the accident. The scenarios modeled concerned tanks filled with 25, 50 and 90 % of liquid. The gas phase is composed of a mixture of air and vapor, considering the partial pressure of the vapor of the stored substance.

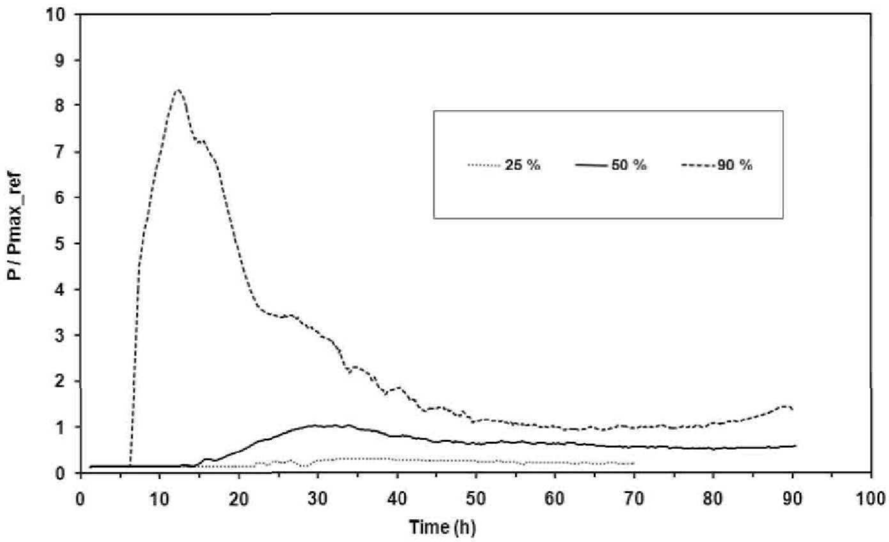

Figure 7. Influence of the tank filling

It seems that an initially full tank leads to a quicker phenomenon, with a really bigger overpressure. This is partially due to the limited amount of gas which is needed to obtain equivalent conditions of pressure in each case. Moreover, the behavior of the system doesn't appear as a linear function of the tank filling. The same study has been done concerning the diameter of the tank:

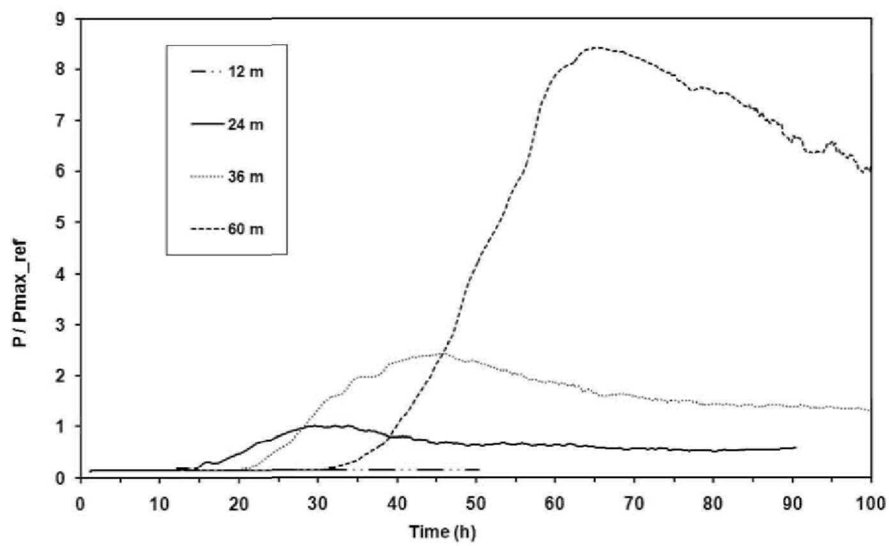

Figure 8. Influence of the tank diameter

Increasing the diameter of the tank has for effect to increase the overpressure obtained. This can be partially explained by the exchange surface between the liquid and gas phase, which increases with bigger diameters. However, as the total volume of liquid increases too, the overpressure is observed later.

The two previous parameters directly impact the area of wetted wall, which seems to be the dominant factor causing the observed peak pressure, due to an efficient heat transfer from the fire. The effect of diameter on time duration seems to also be explained by the ratio wall area / tank volume, which decreases as diameter increases.

The last study done concerned the dimension of the vent. It has overall been done in order to check the behavior of the model.

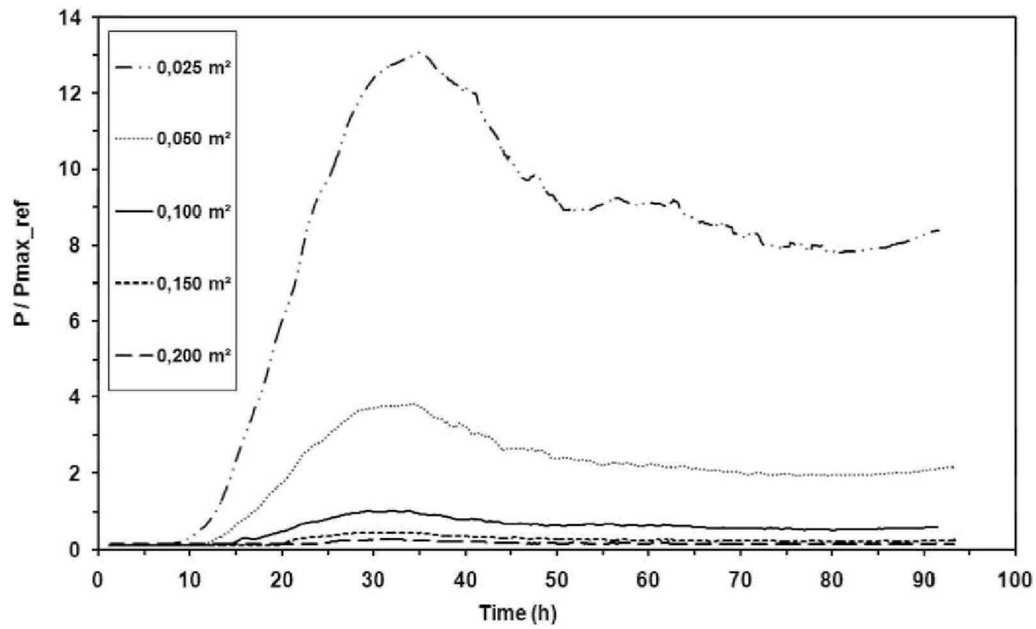

Figure 9. Influence of the vent surface

Results follow the good sense trends: a limitation of the vent size leads to a higher overpressure.

INDUSTRIAL APPLICATION

The results of the previous parametric study have highlighted the predominance of two parameters: the wetted wall area (linked here to the diameter of the tank) and the surface of the vent. In order to establish a general behavior chart, various simulations have been run with different configurations regarding these two input data. The output data will allow to:

- Either in a design phase, calculate the vent size needed to prevent any accident due to pressure increase inside the tank;
- Or for already built tanks, supply input data for the phenomenological study of the potential fireball generated, based on the temperatures mapping in the liquid at the bursting pressure.

For the production of a first general behavior chart, the following conditions were chosen. The fixed parameters are the height of the tank (14 m), the tank wall thickness (10 mm), the filling ratio of the tank (90% of the total height), the substance stored (decane), the maximum radiative flux of the fire (50 kW.m-2) with a progressive loading on the wall. The varying parameters are the vent size and the tank diameter.

A typical result obtained is represented on Figure 10, as a function of time. This curve corresponds to the smallest tank (12 m diameter) with the smallest vent (0,025 m²) studied.

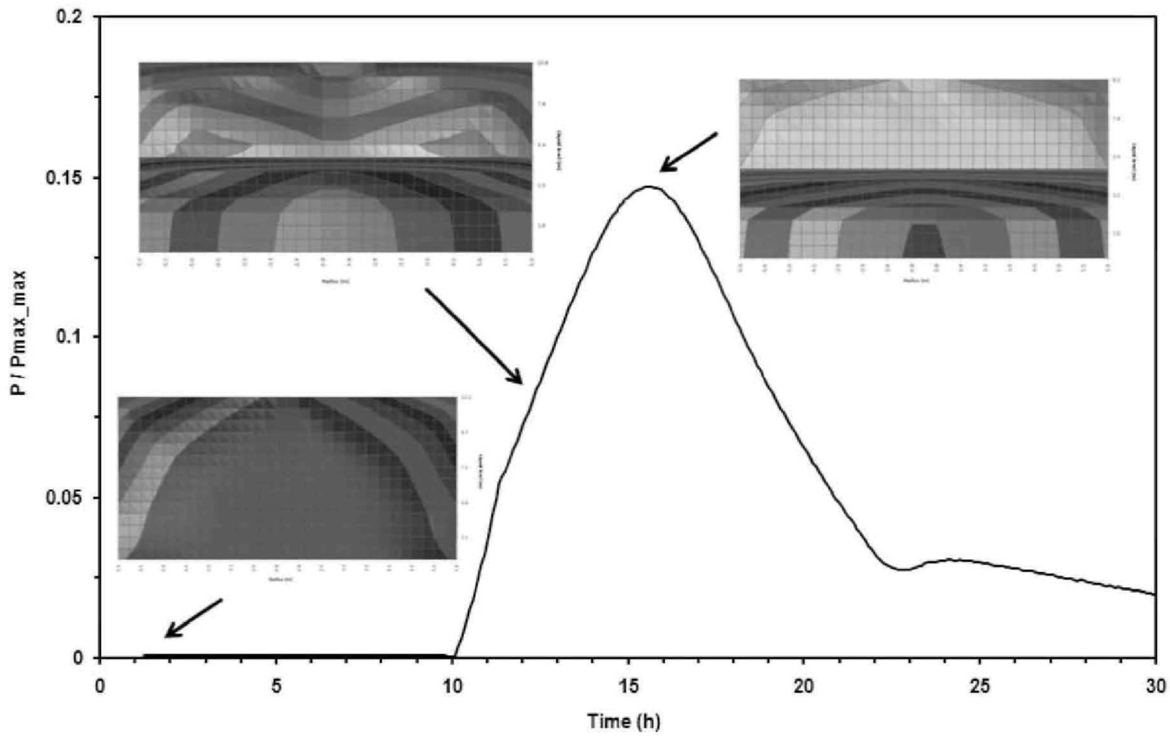

Figure 10. Example of output data

In this Figure, the 2D maps represent the distribution of temperatures in the liquid phase, at different time steps. The "discontinuity" which appears is due to the approach taken to model the fire, with a non uniform loading along the height of the tank. These maps will allow to determine the quantity of liquid which will participate to the potential fire ball at a given failure pressure. Pmax_max is the maximum pressure reached during the parametric study presented in this section, it means for the smallest vent size and maximum tank diameter.

Figure 11 shows the results obtained for the influence of the vent size on the behavior of the pressure, for a 48 m diameter tank. The tank has vents with surfaces varying from 0,025 m² to 0,500 m².

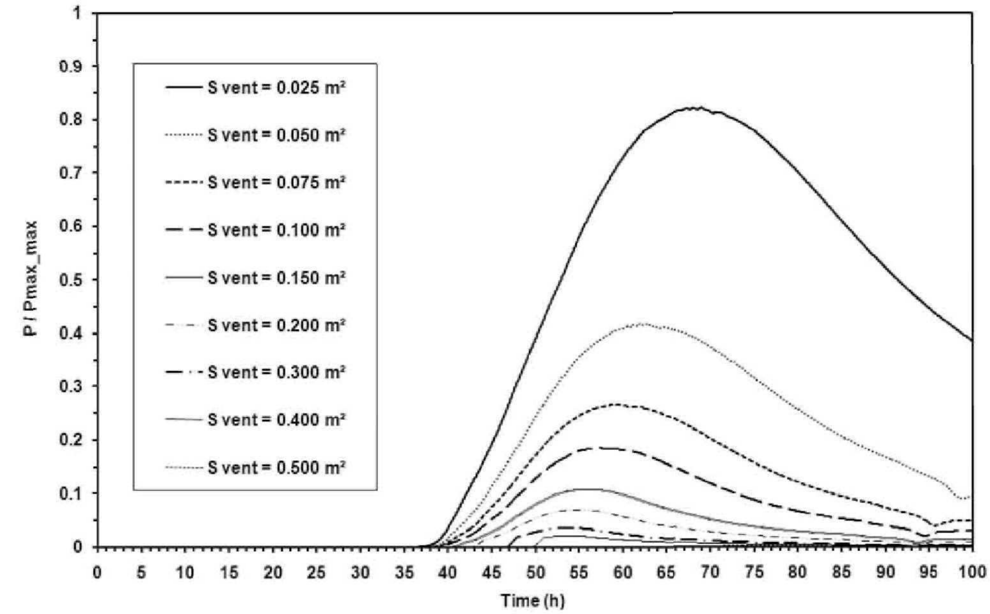

Figure 11. Influence of the vent size for a 48 m diameter tank

The other tanks studied had diameters of 12, 24, 36 and 60 m. By retaining only the maximum pressure obtained during calculations, it is now possible to compile these data in a general behavior chart, as represented in Figure 12.

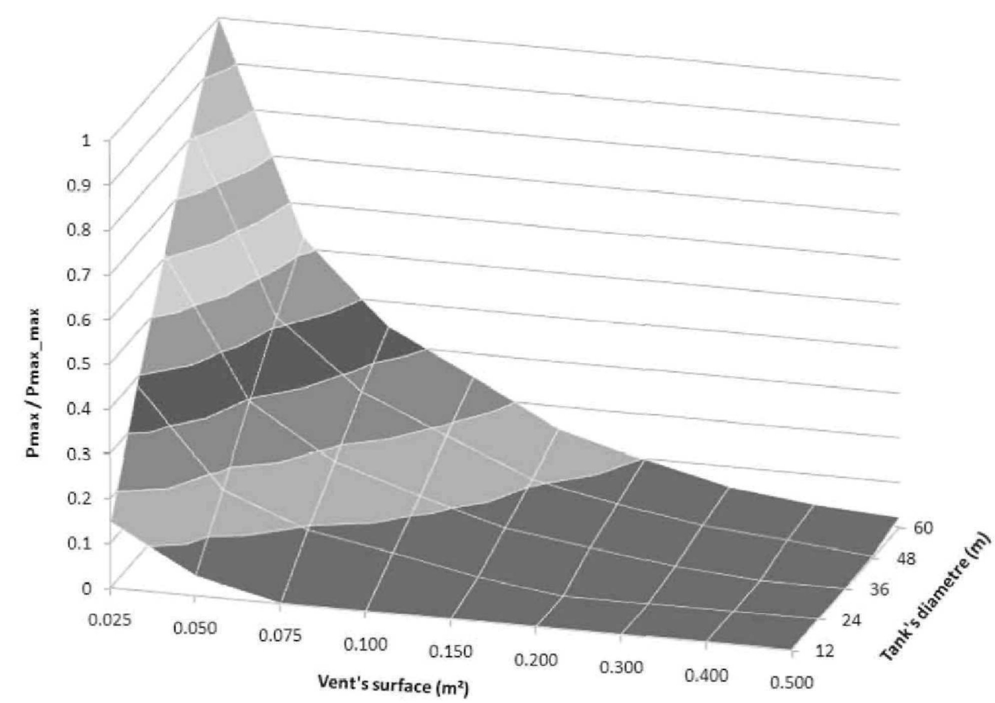

Figure 12. Resulting pressure as a function of tank diameter and vent size

CONCLUSION

The model presented in this paper is a tool developed by INERIS, to determine the surface of vents which should be put in place to compensate the vaporization flow of the content of a fixed roof tank caught in a pool fire. The results obtained with the first parametric studies seem to be consistent with the trends that could be expected. The behavior of the liquid, the heat balance and the kinetic of simulated phenomenon suggest that the computed code works correctly. However, the sensitivity of results to various parameters makes unavoidable the implementation of experimental trials. These parameters have been identified during the development of the model, and the experimental approach will help to adjust them, in order to obtain a model as close as possible to the real behavior. Further to these trials, the next step of this study will be to assess the effects resulting from the rupture of the pressurized tank and from the generation of the fireball.

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